4.4 The Stars

Stars come in many sizes, brightnesses, shapes and colors. In Orion we find the beautiful orange-red Betelgeuse keeping company with the brilliant bluish-white Rigel. In constellation Auriga lies the Sol-like familiar yellow star Capella. The brightest star in Libra, named Zubeneschamali, is naked-eye green in color and is best seen low in the midnight summer sky.[1191]

More than two-thirds of all stars form multiple systems -- double stars, triple stars and more. With a telescope one can observe the gold and blue splendor of g Andromedae, the twin red and green suns of a Hercules, and the exquisite orange, yellow and blue of zCancri.[49] The stars in eclipsing binaries are often extremely near to one another, so close that the tidal force pulls the smaller sun into an ellipsoidal shape. Gigantic beautiful whorls and ribbons of luminous matter flow from one to the other in complex patterns so faint they can only be witnessed visually by the local inhabitants of these systems. Even with our most powerful telescopes we cannot actually see these processes but must infer them from indirect evidence.[20]

Besides color and shape, stars differ markedly in their relative luminosity. This property varies among suns across more than eight orders of magnitude - as much as a hundred thousand times brighter, to more than a thousand times dimmer, than Sol.

If the spectra of a large number of stars are compared, however, certain regularities immediately become apparent. All stars can be divided into relatively few groups whose spectra all look pretty much the same. These are the classes O, B, A, F, G, K, and M. (There are a few others - R, N, S - but these are of lesser importance.)*

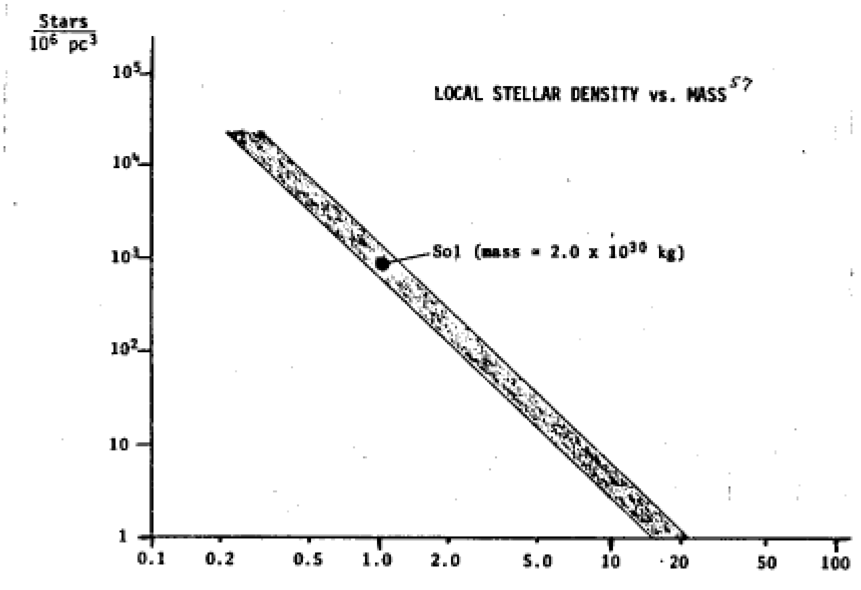
We’ve already seen that the O and B stars are the hot, short-lived, young and massive suns of spiral arm fame. Classes A and F are less hot and have longer lifetimes. Sol is class G. But the majority of all stars fall into the two classes K and M. These are relatively feeble, undistinguished objects, yet they burn little fuel and live extremely long lives - more than ten thousand times longer than their O and B counterparts. Luminosity, then, is a rough index of both the rate of fuel consumption and the life span of a star.[32]

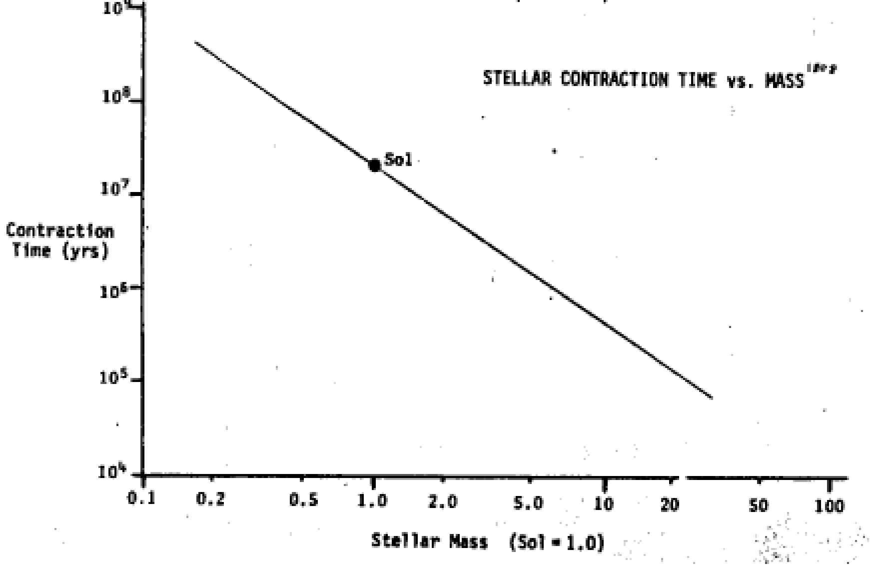
Numbers from zero to nine are used to further subdivide the spectral classes. For instance, a G0 sun is more luminous than a G5, which in turn is brighter than a G9 - the dimmest in the G class. The next-faintest star, of course, would be K0. M suns are the feeblest of all.

The brightest star on record is class O5, since objects from O0 to O4 have not been found. Stars with numbers between zero and four are often referred to as "early," while those with higher numbers are considered "late." Sol, technically a G2 sun, would thus be viewed as an "early spectral class G star."

Stellar mass, in contrast to luminosity, is restricted to within relatively narrow limits (Figure 4.11). Few stars have masses beyond an order of magnitude more or less than Sol’s. There is good reason for this.

Figure 4.11 Stellar number density near Sol, and stellar contraction time, as a function of stellar mass[57,1808]



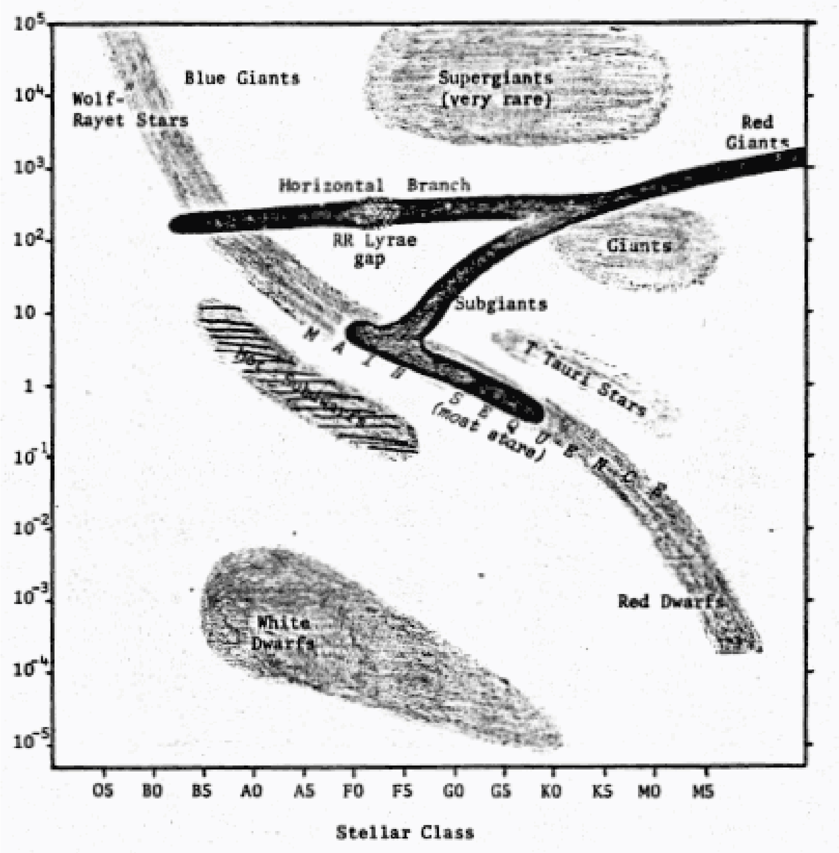


A star in the process of formation is a battleground for two opposing forces which struggle constantly to gain the upper hand. Gravity, which tries to collapse the ball of gas into a small volume with high density, is counteracted by radiation pressure, which grows more intense as the star's thermonuclear furnace kindles and catches. The protostar shrinks to the point where radiation and gravity exactly balance each other, and relative stability is achieved.

Below about 0.01 Msun the ball of gas just sits there, big and cold. Gravitational forces predominate. Internal pressures are just too low for nuclear fires to ignite. Dr. Hong-Yee Chiu at the NASA Institute for Space Studies calculates that stellar mass must be greater than about 0.02 Msun for fusion reactions to be initiated.[1314] This prediction squares well with observations. The lightest stars known - of M9 class - are all at least 0.05 Msun or more. Jupiter, the gas giant planet and possible arrested protostar, masses only 0.001 Msun

In the direction of higher mass, Chiu calculates that if the body exceeds about 30 Msun the radiation pressure must be so great it would literally blow the star apart. Indeed, the largest stars known mass very close to this value.[1314]

The Hertzsprung-Russell diagram (Figure 4.12) is a plot of luminosity as a function of stellar class. About 91% of all stars fall neatly onto a narrow strip running diagonally from top to bottom. This is known as the main sequence.

	Figure 4.12. Hertzsprung-Russell Diagram
Stellar Luminosity (Sol = 1.0) (Solar Luminosity Lsun = 3.84 x 1026 joules/sec) ◍ **Population I stars** ● **Population II stars**	

The main sequence is not an evolutionary track, and is perhaps best thought of as a "house" in which a star resides for most of its life. It is believed that the earliest stages of stellar evolution involve the condensation of a giant cloud of gas and dust many light-years in diameter and massing perhaps 1000 Msun.[1945] As contraction proceeds, the material fragments into many smaller globules until only tiny pieces remain. These units contain a few Msun of matter and measure about a light-year across.

As the protostar shrinks its gravitational potential energy is converted to heat, and after millions of years the object has drawn itself together as a warm cloud about the diameter of our solar system (say, 40 AU). At this point, energy resources are shifted to ionizing instead of heating the gas. The protostar shrinks down to less than 1 AU in perhaps twenty years or so.[1808]

A star suddenly appears in the midst of the whirling gas. We see that the actual contraction phase is very short, lasting less than one percent of the sun's total main sequence lifetime.[57]

These T Tauri stars are stellar newborns, and their luminosity fluctuates erratically with time.[20] Another peculiar feature of such objects is the blowing off of prodigious quantities of matter. It has been estimated that the original protostar loses from 30-50% or more of its starting mass in this fashion.[85,473,1945] Hydrogen burning begins as the T Tauri stage draws to a close, and the star enters the main sequence as a full adult.[1808]

Naturally, not all stars of the same mass cease contraction at the same position on the H-R diagram. Those protostars which are deficient in heavy elements - such as might be the case in globular clusters - arrive at the main sequence at a considerably lower luminosity than most Disk stars. These are called the subdwarfs.[20,1945]

For most normal suns, however, the mass determines both the point of entry onto the main sequence and the length of time of residence there (Table 4.4). Large O and B stars enter high on the sequence, and remain only a few tens of millions of years; the bantamweight K and M suns enter near the bottom and stay for tens of eons. Luminosity on the main sequence increases only very slightly with the passage of time. Sol, for example, has grown only 20% hotter since it left the T Tauri stage five eons ago.[20]

Stars are evicted from the main sequence only when all or most of their hydrogen fuel in the car has been exhausted. With the sharp reduction in radiation pressure the core contracts. Hydrogen gas in the outermost shell begins to burn. Collapse of the core raises the temperature there, so that helium-, carbon-, and ultimately oxygen-burning become possible. The star thus separates into two rather distinct components - diffuse burning shell and dense, hot core.

In this "red giant" stage, the shell of hydrogen may be gradually driven outward leaving a brilliant white core behind. (Stars which have left the main sequence remain red giants for perhaps 1% of their total lifetimes.) This "white dwarf " soon finishes off the remainder of its fuel and all fusion reactions cease. A white dwarf slowly cools to become an in visible black dwarf. Life for Sol-sized stars ends as inauspiciously as it began - as cold, dark matter.

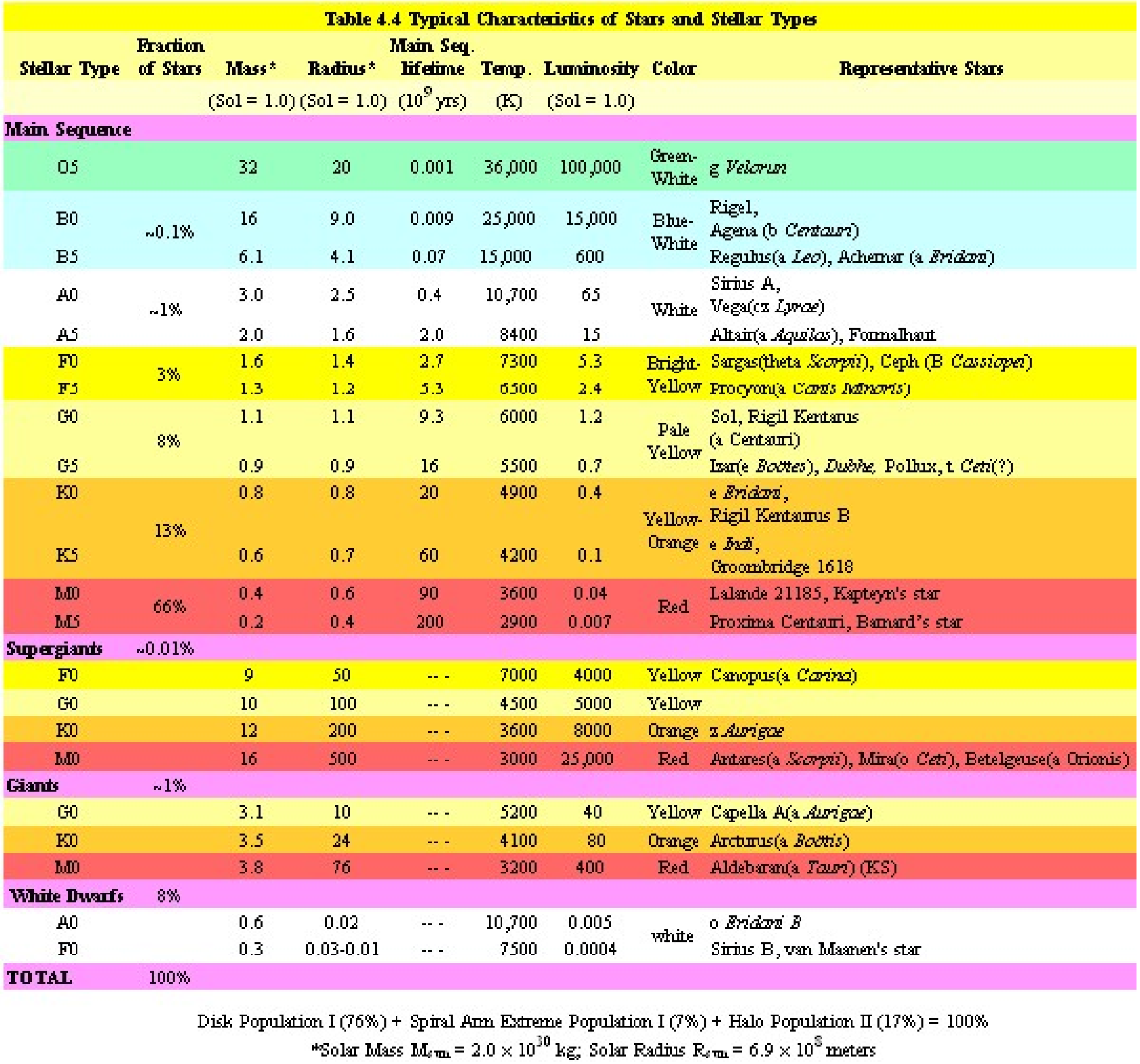


Table 4.4 Typical Characteristics of Stars and Stellar Types

Stellar Type	Fraction of Stars	Mass*	Radius*	Main Seq. lifetime	Temp.	Luminosity	Color	Representative Stars
		(Sol = 1.0)	(Sol = 1.0)	(10^9 yrs)	(K)	(Sol = 1.0)		
Main Sequence								
O5		32	20	0.001	36,000	100,000	Green-White	g *Velorum*
B0	~0.1%	16	9.0	0.009	25,000	15,000	Blue-White	Rigel, Agena (b *Centauri*)
B5		6.1	4.1	0.07	15,000	600		Regulus(a *Leo*), Achernar (a *Eridani*)
A0	~1%	3.0	2.5	0.4	10,700	65	White	Sirius A, Vega(a *Lyrae*)
A5		2.0	1.6	2.0	8400	15		Altair(a *Aquilas*), Formalhaut
F0	3%	1.6	1.4	2.7	7300	5.3	Bright-Yellow	Sargas(theta *Scorpii*), Ceph (B *Cassiopei*)
F5		1.3	1.2	5.3	6500	2.4		Procyon(a *Canis Minoris*)
G0	8%	1.1	1.1	9.3	6000	1.2	Pale Yellow	Sol, Rigil Kentarus (a Centauri)
G5		0.9	0.9	16	5500	0.7		Izar(e *Bootes*), *Dubhe,* Pollux, t *Ceti*(?)
K0	13%	0.8	0.8	20	4900	0.4	Yellow-Orange	e *Eridani*, Rigil Kentaurus B
K5		0.6	0.7	60	4200	0.1		e *Indi*, Groombridge 1618
M0	66%	0.4	0.6	90	3600	0.04	Red	Lalande 21185, Kapteyn's star
M5		0.2	0.4	200	2900	0.007		Proxima Centauri, Barnard's star
Supergiants	~0.01%							
F0		9	50	-- -	7000	4000	Yellow	Canopus(a *Carina*)
G0		10	100	-- -	4500	5000	Yellow	
K0		12	200	-- -	3600	8000	Orange	z *Aurigae*
M0		16	500	-- -	3000	25,000	Red	Antares(a *Scorpii*), Mira(o *Ceti*), Betelgeuse(a Orionis)
Giants	~1%							
G0		3.1	10	-- -	5200	40	Yellow	Capella A(a *Aurigae*)
K0		3.5	24	-- -	4100	80	Orange	Arcturus(a *Bootis*)
M0		3.8	76	-- -	3200	400	Red	Aldebaran(a *Tauri*) (K5)
White Dwarfs	8%							
A0		0.6	0.02	-- -	10,700	0.005	white	o *Eridani B*
F0		0.3	0.03-0.01	-- -	7500	0.0004		Sirius B, van Maanen's star
TOTAL	100%							

Disk Population I (76%) + Spiral Arm Extreme Population I (7%) + Halo Population II (17%) = 100%

*Solar Mass $M_{sun} = 2.0 \times 10^{30}$ kg; Solar Radius $R_{sun} = 6.9 \times 10^{8}$ meters

More massive suns have more spectacular deaths. Stars about 30% heavier than Sol go supernova, leaving behind a small, dense object called a neutron star - essentially a gigantic atomic nucleus, perhaps ten kilometers in diameter, spinning furiously in space.[1214,1314] Densities run about 1014 times higher than that of lead. The pulsar in the Crab Nebula is one of many such objects observed by astronomers in the last decade or so.

Suns with initial masses of 3 Msun or more also supernova, but instead of neutron stars these titanic explosions create spherical nuggets of gravitationally collapsed matter that have come to be known as black holes.** These holes in space represent such a high local mass density that light itself moves too slowly to achieve escape velocity at the surface. Observational astronomers think they've detected one "BH," probably a couple kilometers in diameter, located in the constellation Cygnus.[1970]

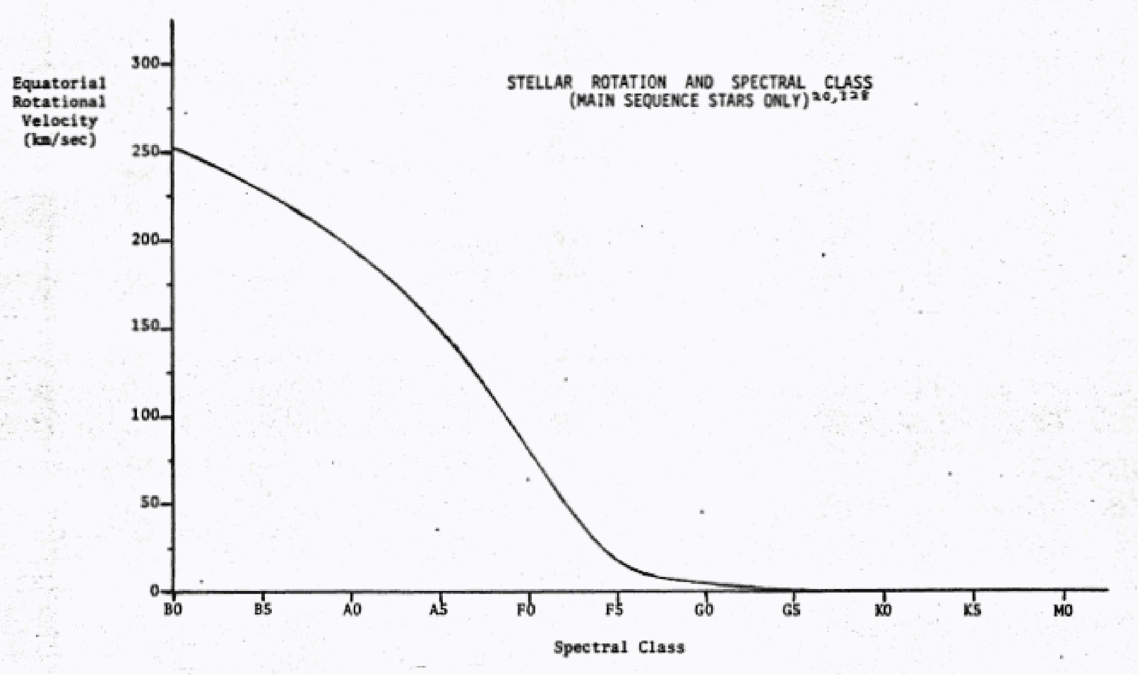
When a star leaves the main sequence, so much energy is released that any life present is probably destroyed. Consequently, as far as the search for extraterrestrial life is concerned, only main sequence stars need be considered as possible cndidates for habitable extrasolar systems.[328] T Tauri objects, giants and supergiants, white and black dwarfs all may be eliminated from consideration. Fortunately, this still leaves us with about three-quarters of all suns in the Galaxy as putative abodes for life.

We know that life required 4.6 eons to arrive at its present stage of development here on Earth. Even if a certain margin of variation is allowed to account for differing speeds of evolution on different planets, the first fossil records of marine invertebrates don’t appear until the opening of the Cambrian Period a mere 600 million years ago. It is plausible to conclude that at least three or four eons - the so-called "genesis time" - may be required on any planet for intelligent life to gain a foothold.[214]

If this is indeed the case, then life will be restricted to stars of class F5 and later.[57,328] Suns of earlier classes remain on the main sequence for less than the critical genesis time of several billion years, rendering improbable the emergence of intelligence.

Another argument in favor of class F5 as the early cutoff point is based on measurements of stellar rotation among the various classes of stars. There appears to be a sharp break at F5 in the amount of angular momentum possessed by suns (Figure 4.13). This conspicuous phenomenon can reasonably be explained by invoking the presence of planets.[1278]

Figure 4.13 Stellar rotation vs. spectral class (Main Sequence stars only)[20,328]



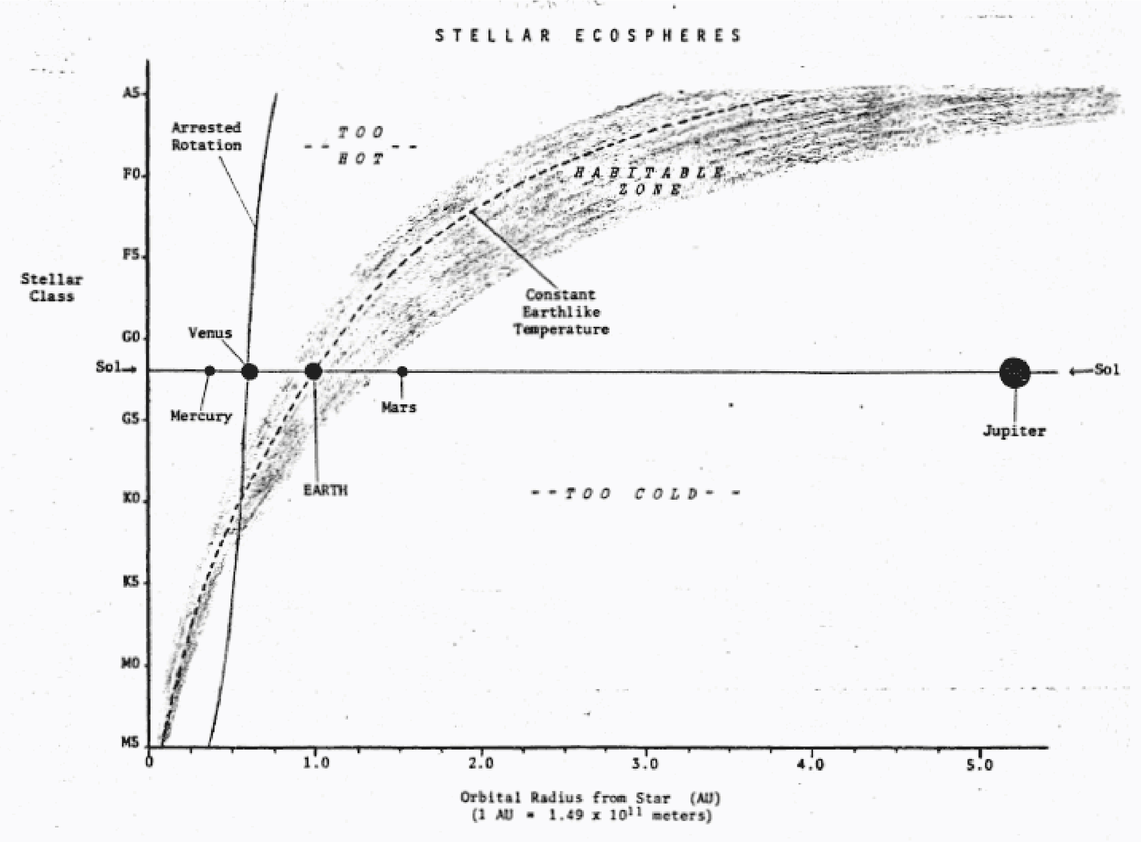
It is suspected that the birth of planetary systems is closely linked to the contraction and evolution of the primary. Approximately 98% of the angular momentum of our solar system is carried by the planets - which represent only 0.2% of the total mass!

The hotter, fast-rotating stars are thought to be devoid of planets because they still retain the high initial rotation rate caused by the condensation of the original protostar. Cooler stars, later than F5, appear to have lost this great rotation somehow. One reasonable interpretation is that, like Sol in our system, these stars invested most of their angular momentum in their planets during the process of solar system formation.[328]

What is the smallest star that can harbor life ? To answer this question we must briefly consider the concept of habitable zones or stellar ecospheres (Figure 4.14). An ecosphere is that region of space surrounding a sun where the radiation is neither too strong nor too feeble to support life. Too close to a star and a planet will fry; too far away, and it will freeze. The habitable zone lies between these two extremes.

Dr. Stephen H. Dole of the Rand Corporation has defined the limits of ecospheres so as to ensure that at least 10% of the surface of a world remains habitable all the time.[214] Dole estimates that to accomplish this the radiation from the primary must be within 35% of Earth-normal. (This may be too pessimistic[57,600] or too optimistic[1907,2031] to suit some, but it's a good first guess.) Of course, the size of the ecosphere will vary from star to star, the less massive dim suns having much smaller zones of habitability than the more massive, brighter ones (Table 4.5). And planets must huddle closer to cooler stars to keep warm; the ecospheres of F stars will lie at considerably greater distances than the zones surrounding, say, class K suns.

Figure 4.14 Stellar ecospheres (habitable zones)



Another argument frequently advanced is that since K and M stars have relatively close ecospheres, planets within these habitable zones will become partially or totally tidally locked to their primary. That is, such planets would rotate extremely slowly; worse, they might become one-face worlds, always presenting only one side to the sun for heat. This could result in the atmosphere freezing out on the cold side[57,214,1908] or other environmental severities.[20]

Stars massing less than 0.7 Msun may have ecospheres so narrow and close as to possess no havens from such rotational arrest.[214] This corresponds roughly to stellar class K3. On the other hand, K2 and earlier stars should have at least a small region within their habitable zones in which tidal braking is much less severe.

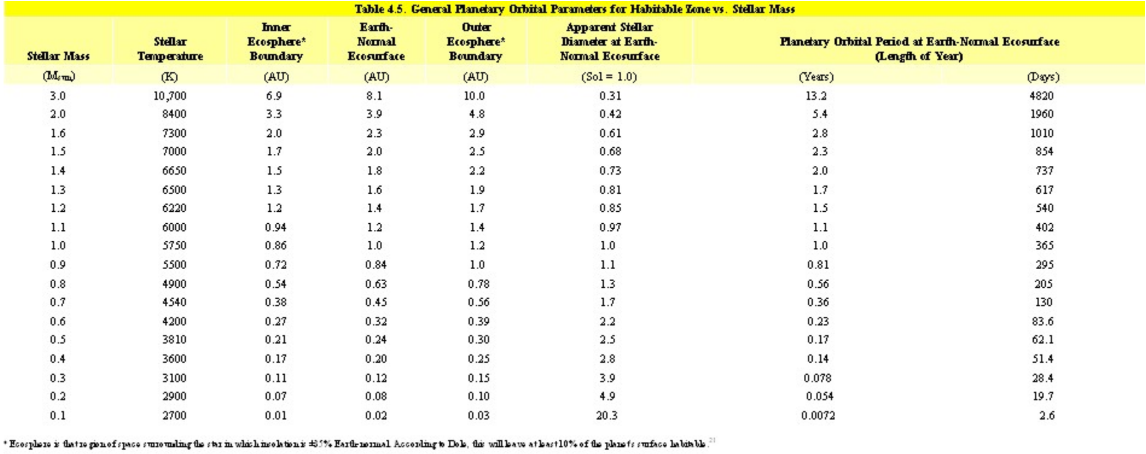


Table 4.5. General Planetary Orbital Parameters for Habitable Zone vs. Stellar Mass

Stellar Mass	Stellar Temperature	Inner Ecosphere* Boundary	Earth-Normal Ecosurface	Outer Ecosphere* Boundary	Apparent Stellar Diameter at Earth-Normal Ecosurface	Planetary Orbital Period at Earth-Normal Ecosurface (Length of Year)	
(M_{sun})	(K)	(AU)	(AU)	(AU)	(Sol = 1.0)	(Years)	(Days)
3.0	10,700	6.9	8.1	10.0	0.31	13.2	4820
2.0	8400	3.3	3.9	4.8	0.42	5.4	1960
1.6	7300	2.0	2.3	2.9	0.61	2.8	1010
1.5	7000	1.7	2.0	2.5	0.68	2.3	854
1.4	6650	1.5	1.8	2.2	0.73	2.0	737
1.3	6500	1.3	1.6	1.9	0.81	1.7	617
1.2	6220	1.2	1.4	1.7	0.85	1.5	540
1.1	6000	0.94	1.2	1.4	0.97	1.1	402
1.0	5750	0.86	1.0	1.2	1.0	1.0	365
0.9	5500	0.72	0.84	1.0	1.1	0.81	295
0.8	4900	0.54	0.63	0.78	1.3	0.56	205
0.7	4540	0.38	0.45	0.56	1.7	0.36	130
0.6	4200	0.27	0.32	0.39	2.2	0.23	83.6
0.5	3810	0.21	0.24	0.30	2.5	0.17	62.1
0.4	3600	0.17	0.20	0.25	2.8	0.14	51.4
0.3	3100	0.11	0.12	0.15	3.9	0.078	28.4
0.2	2900	0.07	0.08	0.10	4.9	0.054	19.7
0.1	2700	0.01	0.02	0.03	20.3	0.0072	2.6

* Ecosphere is that region of space surrounding the star in which insolation is ±35% Earth-normal. According to Dole, this will leave at least 10% of the planet's surface habitable.[21]

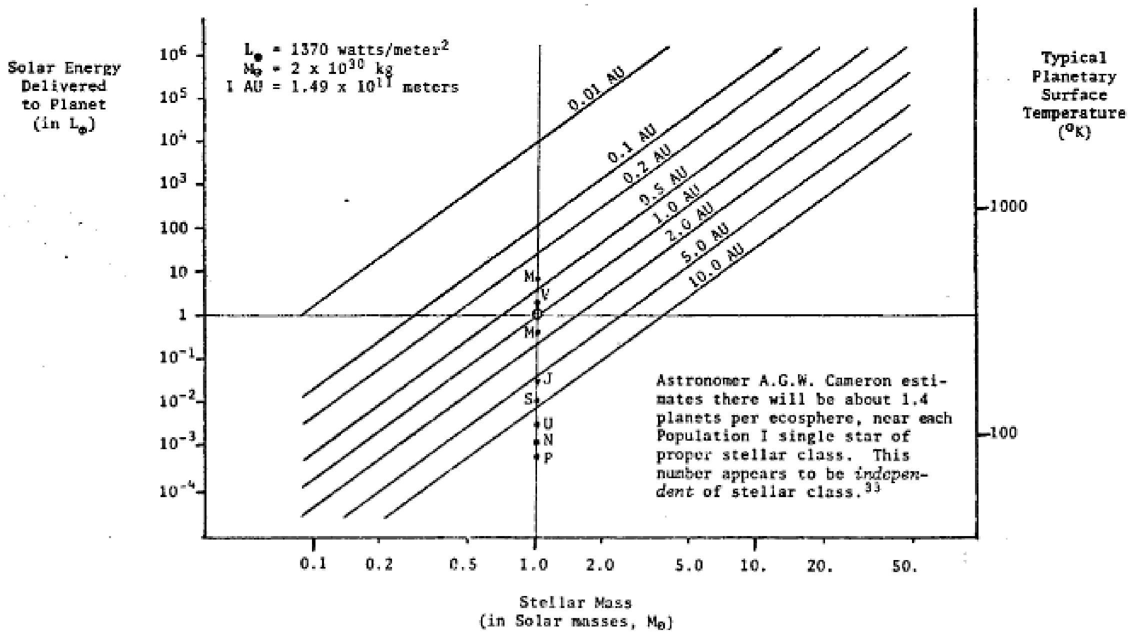
Dr. S.I. Rasool at NASA has also suggested that the atmospheric evolution of planets may be critically dependent on the amount of ultraviolet radiation emitted by the primary.[376] A deficiency in the UV could mean that the hydrogen and helium in the primeval solar system might not have a chance to dissipate from even the innermost planets, which would remain large, gaseous, and quite jovian. (Also, it is believed by some that M suns may be "flare stars," which emit sudden blasts of deadly UV at random intervals.[57,1775])

But there are more serious complications involved in the ultraviolet problem. The steady-state intensity of UV radiation at the surface of the primitive Earth was at least an order of magnitude greater than the next most abundant source of energy.[1017] An ultraviolet deficit might greatly slow or even preclude the origin of life and early biochemical evolution.

It would appear that class K stars radiate at least an order of magnitude less UV than class G, although this has been disputed by some.[57,1775] Class M suns are even more niggardly, emitting less than 1% as much UV as Sol at equivalent locations within their ecospheres. The evidence, while far from conclusive, seems to rule out stars later than early K as possible abodes for life.[214,1018]

As a first approximation, then, we choose to limit ourselves to population I stars in classes F5 through K2 on the main sequence - perhaps 11% of all Milky Way suns (Figure 4.15).

Figure 4.15 Planetary surface temperature inside habitable zones



Astronomer A.G.W. Cameron estimates there will be about 1.4 planets per ecosphere, near each Population I single star of proper stellar class. This number appears to be *independent* of stellar class.[33]

There is one further restriction on our selection of life-supporting stellar environments.[2148] About one-third of all stars occur in pairs (binary stars), and some two-thirds occur in multiples of all kinds (binaries, trinaries, hexastellar systems, etc.).[20] There should be less chance of finding habitable worlds in multiple star systems because of the relatively large variations in planetary surface temperatures (due to the peculiar convoluted orbit traced by a planet circling many suns).[50,1020,1053] The danger of "slingshot" ejection must also be reckoned with.

Calculations reveal that if the components of a binary star system follow relatively circular orbits and are either very close together or very far apart, stable orbits and moderate planetary temperatures are possible.[214]*** Dr. Su-Shu Huang, formerly a physicist at NASA's Goddard Space Flight Center in Washington, made a preliminary determination of habitable orbital configurations near binaries whose components are roughly equivalent in mass.[1020]

If good planetary orbits are to exist, the two stars must lie either less than 0.4L½ AU apart or more than 13L½ AU apart, where L is solar luminosity in Solar units, Lsun.

Of course, if either component of a binary system is class F4 or earlier, then both are unlikely to have been around sufficiently long for intelligent life to have arisen (though planets and simple lifeforms are not precluded). We also must reject population II binaries, as well as those which have a red giant, white dwarf, neutron star or black hole as one member of the pair.[1018]

Dr. T.A. Heppenheimer at the Center for Space Science in California has completed some simple calculations on the formation of planets in binary systems.[1300] His preliminary results indicate that, taking into account the typically large orbital eccentricity (e ~ 0.5) found in binary star systems, the components must actually be separated by more than 30 AU if they are to provide suitable habitats for biology. Apparently about one-third of all F5-K2 binaries within five parsecs of Earth satisfy this requirement.[575,1300,2029]

In conclusion, our quest for life on other worlds should be limited to perhaps 5% of all stars in the Galaxy. The basic search therefore encompasses some ten billion suns, most of which lie in the Disk and outer Core regions of the Milky Way.

* Traditional mneumonic : "Oh Be A Fine Girl, Kiss Me Right Now. Smack !" Suggested non-

sexist mnemonic: "Out Beyond Andromeda, Fiery Gases Kindle Many Red New Stars."[2111] The modern version doesn't seem to be catching on.

** The properties of black holes are fascinating, and many excellent reviews have been written, including those by Thorne,[1965,1966,1967] Penrose,[1968] Kaufmann,[1971] Ruffini and Wheeler,[1969] and Hawking.[2021]

*** It has been suggested that the Trojan points of double stars might be a good place to look for habitable planets.[607]

Chapter 5. General and Comparative Planetology

"I have chosen that part of Philosophy which is most likely to excite curiosity; for what can more concern us, than to know how this world which we in habit is made; and whether there be any other worlds like it, which are also inhabited as this is ?"

- Bernard de Fontenelle, Conversations About the Plurality of Worlds (1686)

"We know the prodigality of Nature. How many acorns are scattered for one that grows to an oak? And need she be more careful of her stars than of her acorns ?"

- Sir Arthur Stanley Eddington (1882-1944), in The Nature of the Physical World (1928)[1549]

"Roll on, thou deep and dark blue Ocean - roll !...
Dark-heaving - boundless, endless, and sublime,
The image of eternity."

- Lord Byron (1788-1824), Childe Harold

"Geologists believed that Mount Lookitthat was geologically recent. A few hundred of thousands of years ago, part of the planet's skin had turned molten. Possibly a convection current in the interior had carried more than ordinarily hot magma up to melt the surface; possibly an asteroid had died a violent, fiery death. A slow extrusion had followed, with viscous magma rising and cooling and rising and cooling until a plateau with fluted sides and an approximately flat top stood forty miles above the surface.

"It had to be recent. Such a preposterous anomaly could not long resist the erosion of Mount Lookitthat's atmosphere."

- Larry Niven, in A Gift from Earth (1968)[231]

Historically, scientists have been willing to populate the Moon, Mars, and even Sol with a great multitude of living beings. But they often were loath to extend this cosmic fecundity to regions outside our own solar system. The main hangup was that until only a few decades ago, the very idea of an abundance of planets circling other stars was scoffed at by most professional astronomers. Sol's family of worlds was believed to be an extreme rarity, if not an absolutely unique event, in the Galaxy.

The cause of this pessimism regarding possible habitats for life in the universe was due in part to the currency of the so-called "catastrophic" theories of solar system formation. These held that the planets were born when a vagabond star passed too close to Sol, ripping away rather sizeable hunks of solar matter. The filaments of star-stuff then condensed into solid worlds, which fortuitously assumed nicely circular orbits around the sun.

The problem with this model is that stars are very far apart in the Disk of the Galaxy, so collisions of this sort must be quite improbable. The catastrophic theories lead to the inevitable conclusion that there are less than perhaps twenty solar systems in the entire Galaxy.[20] This, in turn, implies that few if any habitable worlds exist outside our own solar system.

In the 1930's and early 1940's a dramatic turnabout in attitude occurred.[2038] Young stars in the process of formation were observed to be embedded in dense dust clouds lacked by older stars. Young stars were also seen to possess large amounts of angular momentum which older stars don't have. Nearby suns were observed to wobble very slightly from side to side as they traveled through space, as if thrown off balance by the presence of a heavy, unseen companion. These and other observations were hailed as strong evidence that many, if not all stars, are accompanied by a planetary entourage.

Today, astronomers think of solar system formation, not as an exceedingly rare event, but as a normal and common adjunct to stellar evolution. With two hundred billion stars in our Milky Way Galaxy, and more than a billion galaxies in the universe at large, the number of possible habitats for life becomes truly staggering. If there are 1020 planetary systems throughout the cosmos, then on the average more than a million of them are born every hour.[20]

The central objective of the science of general planetology is fairly straightforward : To study the physical and chemical properties of all non-self-luminous material bodies, whether they occur in our own system or in orbit around some distant star.* A planet, consequently, is defined as any aggregate of matter possessing insufficient mass to sustain spontaneous thermonuclear reactions in its interior.[214]

Xenology has two questions to ask of planetology. First, exactly how common are solar systems in the Galaxy ? How many of them are there, under what conditions do they arise, and where are we most likely to find them? Questions of planetary evolution and distribution are of immense xenological importance, both in the practical sense of knowing where to search for extraterrestrial life and in the theoretical sense of being able to assess the uniqueness of life on Earth.

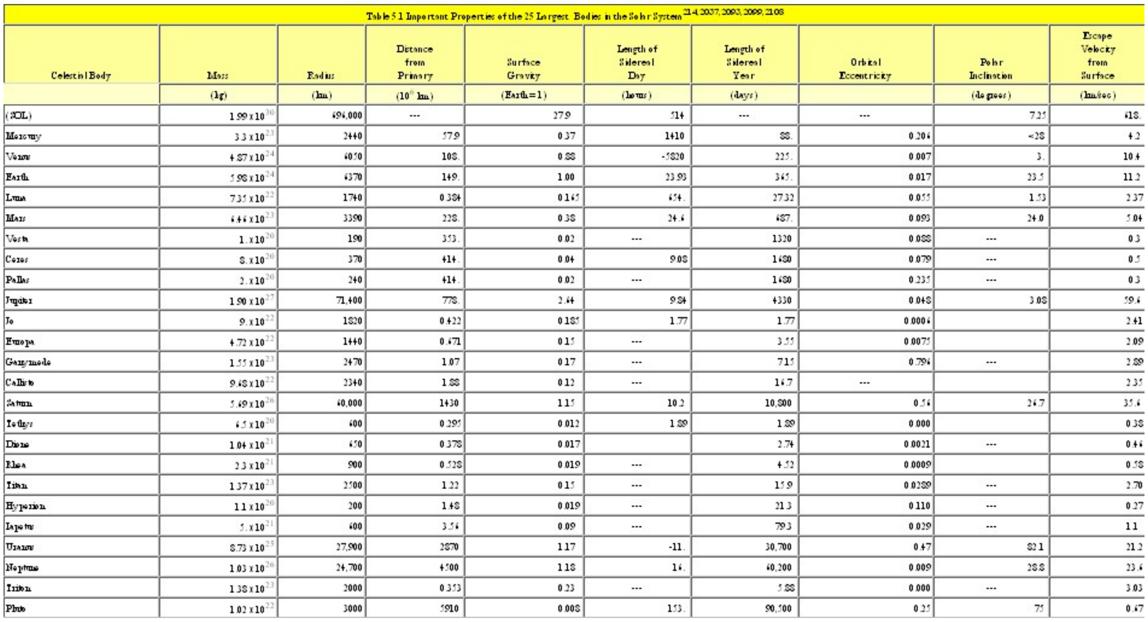


Table 5.1 Important Properties of the 25 Largest Bodies in the Solar System[214,2037,2093,2099,2108]

Celestial Body	Mass	Radius	Distance from Primary	Surface Gravity	Length of Sidereal Day	Length of Sidereal Year	Orbital Eccentricity	Polar Inclination	Escape Velocity from Surface
	(kg)	(km)	(10^6 km)	(Earth=1)	(hours)	(days)		(degrees)	(km/sec)
(SOL)	1.99×10^{30}	696,000	---	27.9	514	---	---	7.25	618.
Mercury	3.3×10^{23}	2440	57.9	0.37	1410	88.	0.206	<28	4.2
Venus	4.87×10^{24}	6050	108.	0.88	-5820	225.	0.007	3.	10.4
Earth	5.98×10^{24}	6370	149.	1.00	23.93	365.	0.017	23.5	11.2
Luna	7.35×10^{22}	1740	0.384	0.165	654.	27.32	0.055	1.53	2.37
Mars	6.46×10^{23}	3390	228.	0.38	24.6	687.	0.093	24.0	5.04
Vesta	$1. \times 10^{20}$	190	353.	0.02	---	1320	0.088	---	0.3
Ceres	$8. \times 10^{20}$	370	414.	0.04	9.08	1680	0.079	---	0.5
Pallas	$2. \times 10^{20}$	240	414.	0.02	---	1680	0.235	---	0.3
Jupiter	1.90×10^{27}	71,400	778.	2.64	9.84	4330	0.048	3.08	59.6
Io	$9. \times 10^{22}$	1820	0.422	0.185	1.77	1.77	0.0006		2.41
Europa	4.72×10^{22}	1440	0.671	0.15	---	3.55	0.0075		2.09
Ganymede	1.55×10^{23}	2470	1.07	0.17	---	715	0.796	---	2.89
Callisto	9.68×10^{22}	2340	1.88	0.12	---	16.7	---		2.35
Saturn	5.69×10^{26}	60,000	1430	1.15	10.2	10,800	0.56	26.7	35.6
Tethys	6.5×10^{20}	600	0.295	0.012	1.89	1.89	0.000		0.38
Dione	1.04×10^{21}	650	0.378	0.017		2.74	0.0021	---	0.46
Rhea	2.3×10^{21}	900	0.528	0.019	---	4.52	0.0009		0.58
Titan	1.37×10^{23}	2500	1.22	0.15	---	15.9	0.0289	---	2.70
Hyperion	1.1×10^{20}	200	1.48	0.019	---	21.3	0.110	---	0.27
Iapetus	$5. \times 10^{21}$	600	3.56	0.09	---	79.3	0.029	---	1.1
Uranus	8.73×10^{25}	27,900	2870	1.17	-11.	30,700	0.47	82.1	21.2
Neptune	1.03×10^{26}	24,700	4500	1.18	16.	60,200	0.009	28.8	23.6
Triton	1.38×10^{23}	2000	0.353	0.23	---	5.88	0.000	---	3.03
Pluto	1.02×10^{22}	3000	5910	0.008	153.	90,500	0.25	75	0.67

The second question posed by xenologists is whether or not our solar system (Table 5.1) and home planet (Table 5.2) are "typical" ones. This is basically a test of the Hypothesis of Mediocrity. Are conditions here roughly the same as on worlds circling other suns, or are things vastly different? What is the allowable range of planetary characteristics such as surface temperature, pressure, gravity, atmospheric composition, lithospheric structure, meteorology, seismology, and so forth (Figure 5.1) ? Virtually anything we can learn about a planet enhances our understanding of the lifeforms indigenous thereto. It has been said that there is no property of a planet that is not of some xenological significance.[630]

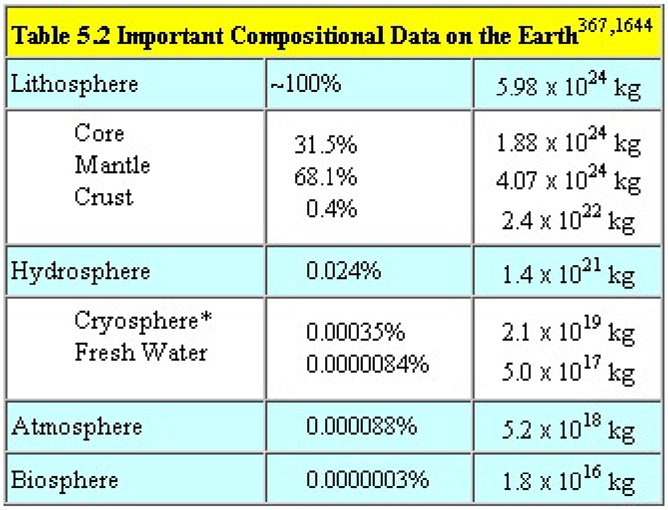
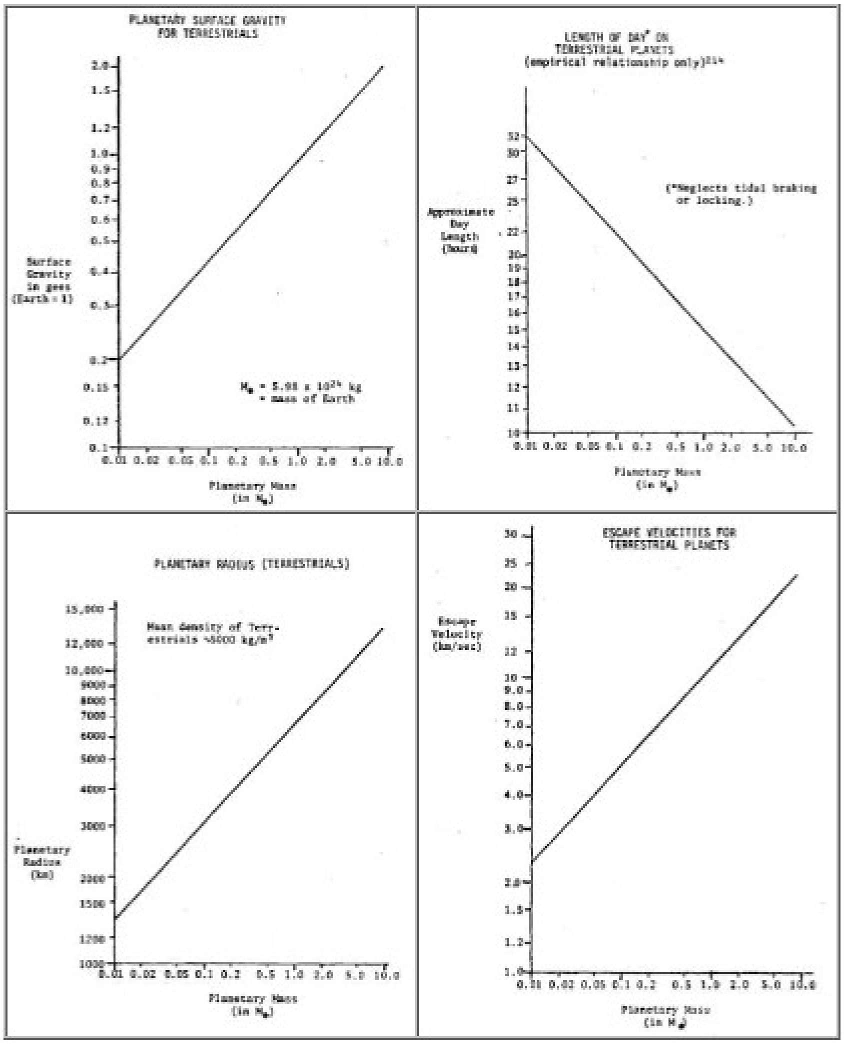


Table 5.2 Important Compositional Data on the Earth[367,1644]		
Lithosphere	~100%	5.98 x 10^{24} kg
Core Mantle Crust	31.5% 68.1% 0.4%	1.88 x 10^{24} kg 4.07 x 10^{24} kg 2.4 x 10^{22} kg
Hydrosphere	0.024%	1.4 x 10^{21} kg
Cryosphere* Fresh Water	0.00035% 0.0000084%	2.1 x 10^{19} kg 5.0 x 10^{17} kg
Atmosphere	0.000088%	5.2 x 10^{18} kg
Biosphere	0.0000003%	1.8 x 10^{16} kg

*Cryosphere: The polar masses of snow and ice, together with the glaciers of the world.

Figure 5.1 Estimated Ranges of Some Interesting Properties for Terrestrial-type Planets



* The reader is strongly advised to peruse a copy of Stephen Dole's Habitable Planets for Man,[214] which is an excellent introduction to general planetology with an eye to the specific problem of finding human-habitable worlds.

5.1 Planetary Evolution

To decide just how abundant planets are in the Galaxy, the most logical place to start is with planetary evolution theory. If we can specify conditions conducive to the birth and development of solar systems, we may then compare these requirements to the observed Galactic environment and form a reasonable opinion as to the likelihood and frequency of planet formation.

Unfortunately, the array of historical planetary evolution schemes[20,2033,2109] and the ongoing proliferation of both mundane[1278] and unusual[816,1264] models in modern times are beyond the scope of this book. We will not deal with them at length here, especially since excellent and comprehensive reviews are readily available elsewhere.[20,600,816,1278,2025,2033]

While all conclusions regarding planetary formation even today must be viewed as tentative, it appears that accretion models suffice to account for most of the observed properties of bodies in our solar system. In one theory which is gaining wider acceptance, a large, slowly rotating cloud of interstellar gas and dust about a light-year in diameter begins to slowly shrink. As it draws itself together gravitationally over a period of perhaps ten million years,[1945] it becomes denser. Were it merely a glob of ordinary neutral gas, it would end up as a small, rapidly rotating ball of hydrogen. Most of its mass would be flung away unceremoniously - and there would be no planets.[1549]

But radiation generated during the contraction of the hydrogen ionizes the gas, converting it into a plasma -- an electrically-charged, highly conductive but tenuous fluid. The Swedish physicist Hannes Alfvén, of the Royal Institute of Technology in Stockholm, was the first to demonstrate a viable mechanism by which angular momentum could be readily transferred from the protostar (the contracting solar nebula) to the surrounding plasma medium. This was fortunate indeed, because until that time a major problem had been to figure out why the planets (with 0.2% of the solar system's mass) should carry roughly 98% of the total angular momentum.

The magnetic coupling concept announced by Alfvén, and later wielded into a classical theory by world-famous astronomer Fred Hoyle, goes something like this: As the protostar collapses, its magnetic field lines of force are dragged closer together but are held firmly in place. Since the infalling clouds are ionized, the field lines are "glued" to the incoming particles. Thus the protostar's magnetism is coupled directly to the solar nebula; when the protostar tries to speed up as it contracts, the external medium resists the attempt and absorbs the angular momentum itself. The final result is a small, still slowly turning protostar, surrounded by a rapidly rotating disk of matter.

(This theory helps to explain the observed sudden drop-off in stellar rotation later than spectral class F5 (see Chapter 4). Massive, hot stars earlier than F5 apparently are unable to "glue" the magnetic field lines as tightly as cooler suns can. As a result, the field lines wrap themselves uselessly around these bright stars and fail to effect a momentum transfer to the solar nebula. There is no accretion, no planets form, and the protostar retains much of its original rotation. Stars earlier than F5 are thus less likely to spawn worlds than later-class suns.)

The planets themselves form in the disk of matter surrounding the protostar. This tenuous material probably consists of 98% hydrogen and helium, 2% heavier elements - much like the composition of Sol today. As the cloud becomes denser, gases and dust particles begin to adhere and condense to form tiny grains. Clumping of the grains in not unlikely, because such grains are believed to have a fluffy snowflake-like structure.[2038] By the time the development of the protostar gets into full swing, these particles have become millimeter- or centimeter-sized - small cosmic pebbles which naturally tend to gravitate toward the midplane of the nebula. The time required for this downfall is no longer than 10-100 years, and the nebular disk thus created probably measures on the order of 1 AU thick and 100 AU in diameter at this point.[2051]

The disk material must accrete quickly into bodies large enough to avoid the pressure of the inrushing gases in the plane. Were the grains unable to pull themselves into boulder-sized chunks, most of the matter would be swept remorselessly into the yawning solar “vacuum cleaner” at the rotational center of the accretion disk.[33] A means has been proposed to solve this problem, called the “Goldreich-Ward instability mechanism.” According to this theory, a powerful gravitational instability can appear in the plane of the disk provided the cosmic pebbles are not moving too fast with respect to one another.[2038]

Calculations show that this instability should be sufficient to cause aggregation within the thin sheet of pebbles into hundred-ton bodies with the diameters of asteroids - say, one to ten kilometers. Higher-order clustering might then ensue as these bodies begin collecting each other up by collision. This epoch of titanic surface impacts must be reflected in the cratering record we see on the Moon, Mercury, and elsewhere. In our solar system, such impacts were intense during the first 100-500 million years but rapidly tapered off to their present low level about four eons ago.[225,2063]

Two general classes of planet are found forming in the accretion disk. These are jovians (Jupiter-like, gas giants, mostly hydrogen and helium) and terrestrials (Earth-like, rocky crust, dense metal core). The terrestrials tend to appear nearest to the protostar, in the hottest regions of the solar nebula. They are the result of simple mass accretion to build up small, rocky, dense bodies.

The jovians are formed far from the central regions. A small, heavy core serves as a seedling for the accumulation of vast quantities of material. The true jovians - such as Saturn and Jupiter - develop such massive central bodies that they cause the nebular gas to destabilize and condense into a thick, dense shell. This represents most of the final planetary mass. Jovians act much like miniature protostars, voraciously sweeping the nearby space clean of gas and dust.[2051] The subjovians - represented by Uranus and Neptune in our system - don’t have nearly so massive a core as the jovians. Thus, they can retain only those gases normally gravitationally concentrated near the planetary centrum. Subjovians do not grow as large as jovians.

This behavior can be explained in part by the process of differentiation of chemical elements in the condensing solar nebula. According to the detailed hydrodynamic model created by A. G. W. Cameron and his colleagues at the Harvard College Observatory, subjovians tend to form in the outermost regions of the nebula where the pressures are only about 10^{-7} atm* and the temperatures under 100 K. Matter there consists largely of interstellar grains, mostly water-ice condensed upon a small rocky substrate.

Uranus and Neptune, then, consist mostly of ice with a little bit of rock. When sufficient mass has accreted, these bodies can gravitationally draw in some of the solar nebula for atmosphere. Hydrogen and helium will thus comprise perhaps 20% of the total mass of subjovian bodies.[2051] Comets are believed to have originated under similar conditions.[2038]

Jovians are found closer to the swollen protostar. Most likely they occur in a region where the pressure is about 10^{-6} atm and temperatures are 100-200 K or more. At such high temperatures the ice evaporates, leaving only rocky materials to condense. However, due to the higher pressures there is more material around, and it turns out that accretion proceeds faster. This leads to the aforementioned instability and sudden, massive gas collection from the nebula.[2051]

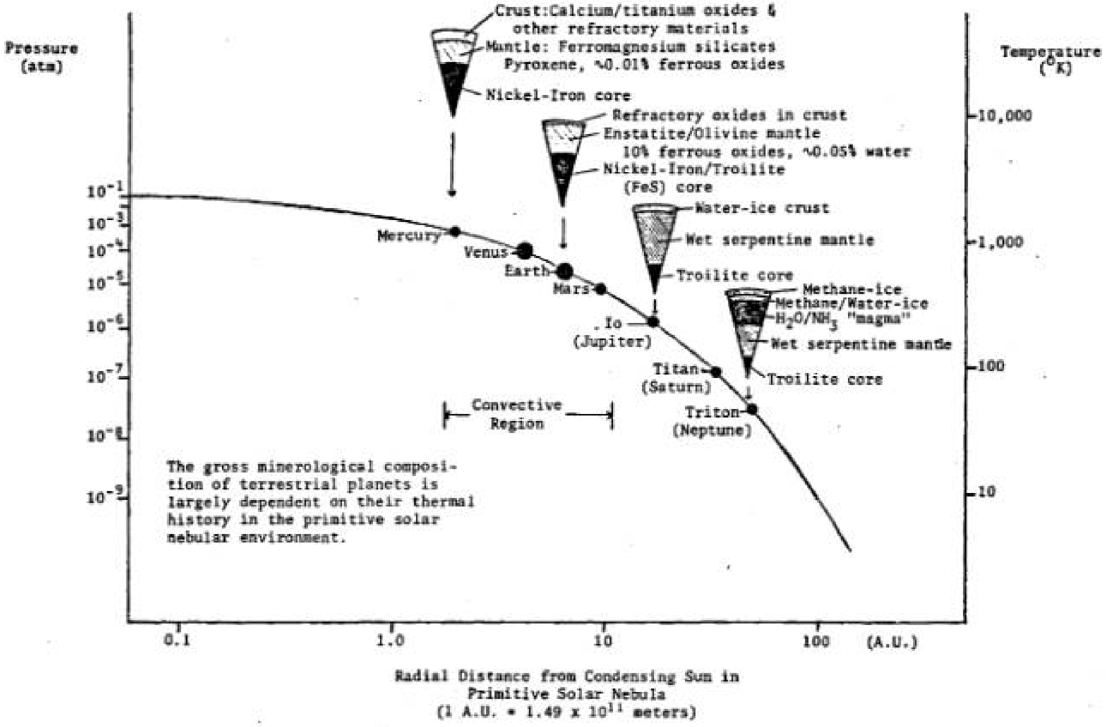
The amounts of gas gobbled by a jovian during this period is astounding. In fact, it appears that even now, 4.6 eons later, Jupiter and Saturn are still in the process of “swallowing” their great feast of hydrogen and helium. Both worlds emit roughly three times more energy than they receive from Sol.[2096,210] This heat is due to the slow collapse of the planets gravitationally.[598,2032,2048,2057] (The shrinkage amounts to about 1 millimeter per year.[2032])

The terrestrials form closest to the protosun, where pressures range from 10^{-5} to 10^{-4} atm and the temperature climbs from 200 K to well over 1400 K.[1564] It is a region of very high convection, so the matter is kept well-stirred. Only small cores with miniscule amounts of nebular gas can accrete. (The extent of this growth restriction is made more clear if we consider stripping the jovians down to their heavy elements. If we did this, we'd find both Jupiter and Saturn with 15-20 Mearth (Earth-masses) of heavies.[2091,2096,2098] This is far more than Earth, the most massive terrestrial world in our system.) Total accretion time for terrestrials probably runs on the order of a thousand to a million years.[2043,2044]

We see that the bulk composition of planets in any single-sun system should follow a quite regular, orderly progression (Figure 5.2). The innermost worlds will consist of the most refractory matter, with the planets at progressively greater distances from the primary consisting of the less refractory materials.[22]

To sum up : We expect that planets lying within or close to the habitable zones of stars will be generally terrestrial in character. Far outside the habitable zone at great distance from the sun, jovians and subjovians put in an appearance. And no planets will be found closer to a star than perhaps one-quarter of the distance to the center of the habitable zone. No substance found in the solar nebula could condense in the extreme heat encountered there.

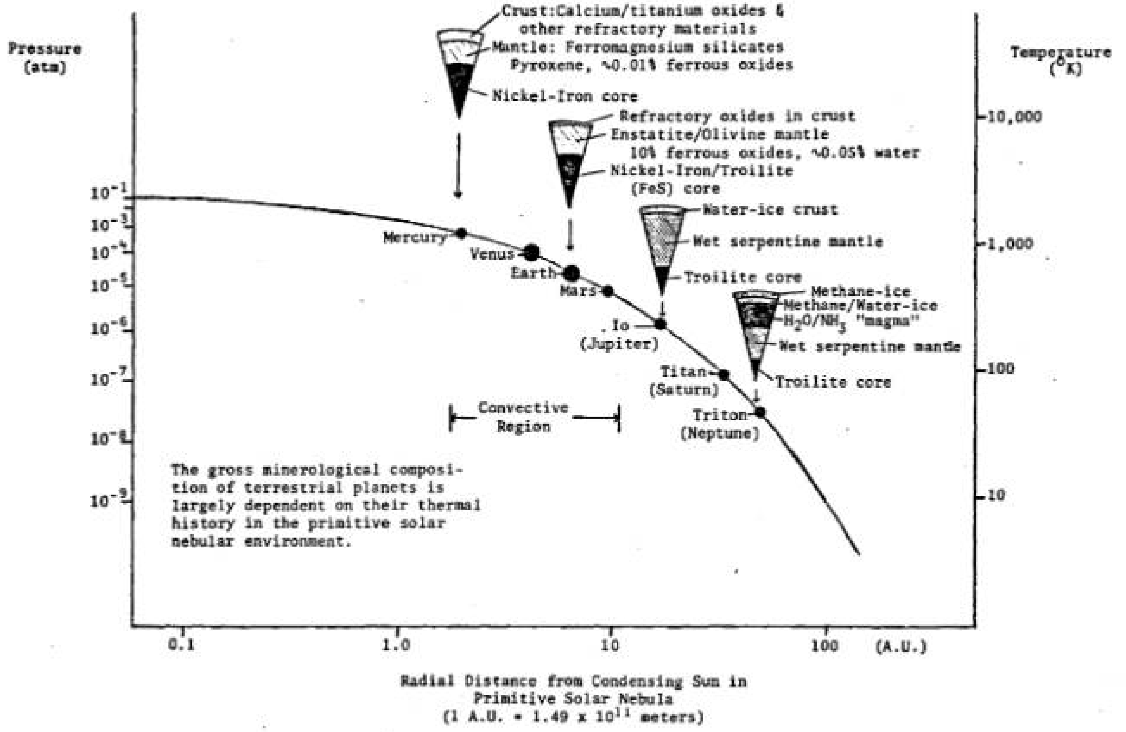
Figure 5.2 Condensation in the Primitive Solar Nebula[2049,2050,2051]



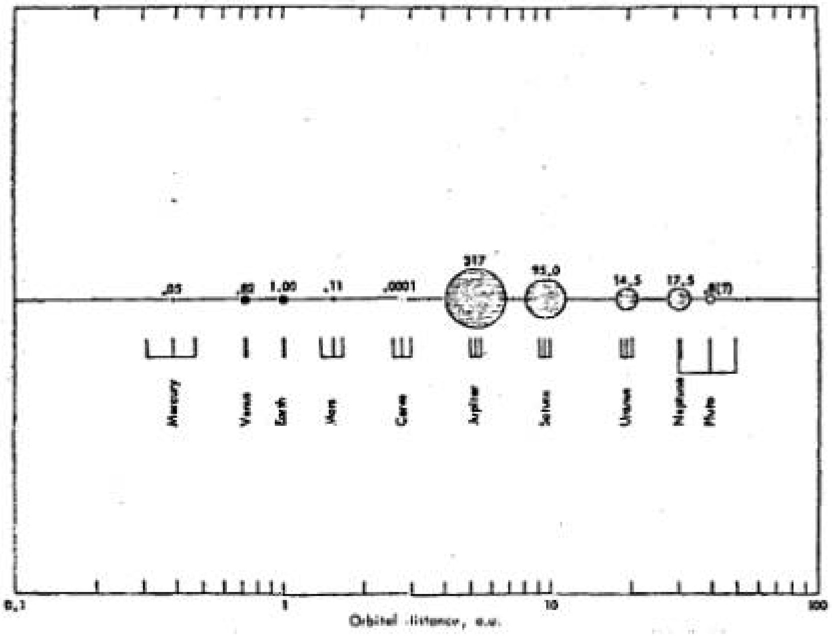
The fundamental correctness of the accretion model has been tentatively verified by Stephen H. Dole of the Rand Corporation.[1258] Dole set up a computer program to simulate the primitive solar system in the process of formation. Accretion nuclei with random orbits are shot into a nebula surrounding a theoretical protostar of 1 Msun Nuclei aggregate dust in the nebula, assumed to be 2% of the total by mass, until a specified critical mass is reached beyond which gas can be accumulated as well. The growing planetesimals coalesce if their orbits cross or if they come too close. Nuclei continue to be injected until all dust has been swept from the system. The model is simplistic, to be sure,[2037] and yet the results are most intriguing.

Despite the fact that Dole varied the initial conditions considerably, the final products always seemed remarkably similar (Figure 5.3). After each run, the end result was a solar system which looked much like our own. The total number of worlds formed varied from seven to thirteen, and the Titus-Bode "law"[1254,1304] of planetary orbital spacing (so well-known to beginning astronomy students) seemed to hold up approximately in all cases.[2054] While every such system is quite unique, the surprising thing is that each shares many features of Sol's system and yields results consonant with accretive evolutionary theories.

Figure 5.3 Results of Computer Simulations of Planetary Formation[1258]



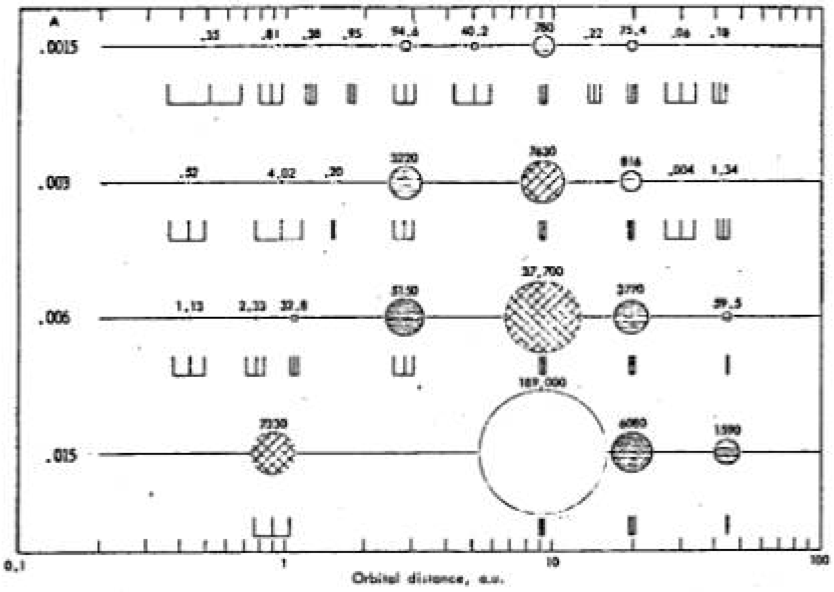
Above are a few examples (among hundreds) of planetary systems synthesized by Stephen Dole's computer model. The sun is at the far left in the diagram and is omitted for clarity. Planets, their orbital distances from their sun, planetary masses and orbital eccentricities all are shown. For comparison, our own solar system is diagrammed similarly below. Note the overall similarities: Terrestrials in close, jovians further out. Solid, filled-in circles represent terrestrial worlds; gas giants are represented by horizontal shading.



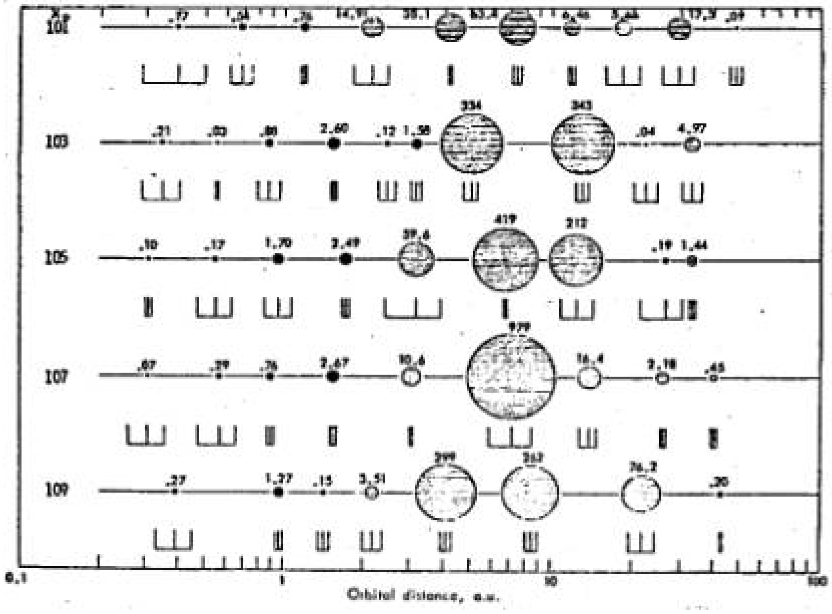
Dole’s program generated another unexpected result. It has long been suspected that the processes which give rise to binary and multiple star systems may actually preclude the formation of planets.[20,1300] In our Galaxy, the average separation of binary components is about 20 AU, corresponding roughly to the orbital distances of the jovian gas giants in our solar system. (Jupiter and Saturn have often been called “failed stars.”[2048] In this view, we narrowly missed out on finding ourselves in the middle of a triple star system.)

By increasing the density of the initial protocloud an order of magnitude higher than before, Dole’s program generated larger and larger jovians (Figure 5.4). Eventually the threshold between planetology and astrophysics was crossed. In one high-density run, a class K6 orange dwarf star appears near Saturn’s present orbit, along with two superjovians and a faint red dwarf further sunward. No terrestrials are formed.

Figure 5.4 Computer Synthesis of Multiple-Star Systems[1258]



Examples of binary and multiple star systems generated by Stephen Dole's computer model are shown above. As the coefficient of density, A, is increased by a factor of ten, terrestrial worlds disappear and the jovians accrete into larger and larger masses, eventually becoming a few self-luminous stars. (Density, A, is measured in solar masses per cubic AU.) Terrestrials are represented as solid circles, jovians by horizontal shading, red dwarf stars by cross-hatching, and the open circle represents a class K6 orange dwarf star. Another set of sample solar systems is included below for comparison.



As Dole says, the general trend is clear. Jovians multiply at the expense of terrestrials. An increase of one critical parameter - the nebular density - may well result in the generation of binary and multiple star systems to the eventual exclusion of terrestrial worlds.[1258]

Both theoretical and numerical accretion models of solar system formation suggest that planets are probably the rule rather than the exception, and that terrestrials should form near most single stars in the inner regions of the solar nebula. This augurs well for the abundance of habitable worlds and extraterrestrial life in the Galaxy.

* one atmosphere (1 atm) = sea level air pressure at Earth's surface.

5.2 Thalassogens

Life on Earth is dependent upon the oceans for both its origin and its evolutionary development. The early organic compounds which ultimately gave rise to living organisms were stirred and stewed in the primitive seas - our entire biological character is molded by the properties of water. Indeed, it is difficult for biochemists to imagine that life could have had its origin in any other medium. Complex chemical reactions must have a reasonable chance of occurring. A liquid medium of some kind is required, capable of dissolving salts and other compounds and then commingling them in the degree of intimacy required for the origin of life. While it is certainly more, water in this sense may be viewed as a "catalyst" of life.

But must conditions on other worlds exactly parallel those found on Earth ? Is water the only possible fluid in which life may originate ? We don't really know the answer to this question (see Chapter 8). Of interest to us here, however, is whatever light can be shed on the problem by the science of planetology.

Isaac Asimov has coined the term "thalassogen," by which he refers to any substance capable of forming a planetary ocean.[1399] Looking for possible thalassogens is somewhat broader than the search for liquids that can sustain life, because some of them may turn out to be anathemic to all conceivable biochemistries. But the planetologists' quest for thalassogens is certainly an excellent starting point for our inquiry.

What substances are available for ocean-building ? There are two characteristics which must be possessed by seas on any planet in our Galaxy. First of all, the very elements comprising the thalassogen molecules must be relatively abundant in the universe (Table 5.3). For instance, the element mercury is a liquid at normal temperatures and so might be considered as a thalassogen. However, its abundance cosmically is only about 0.000000001% of all atoms, which is hardly enough to cover a world the size of Earth to a depth of a millimeter or so.[39,1413]

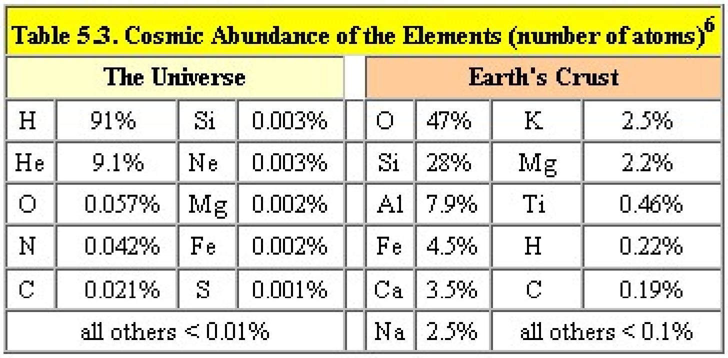


Table 5.3. Cosmic Abundance of the Elements (number of atoms)[6]

The Universe				Earth's Crust			
H	91%	Si	0.003%	O	47%	K	2.5%
He	9.1%	Ne	0.003%	Si	28%	Mg	2.2%
O	0.057%	Mg	0.002%	Al	7.9%	Ti	0.46%
N	0.042%	Fe	0.002%	Fe	4.5%	H	0.22%
C	0.021%	S	0.001%	Ca	3.5%	C	0.19%
all others < 0.01%				Na	2.5%	all others < 0.1%	

How about oceans of dimethyl butanol ? The atoms which make up this substance - carbon, hydrogen, and oxygen - are certainly among the most plentiful in the universe. Unfortunately, the compound is subject to numerous degradations by heat and chemical interactions, and is chemically unlikely to be synthesized in oceanic quantities. So dimethyl butanol must remain relatively scarce on planetary surfaces, despite the ubiquity of its constituent elements.

A molecule must therefore be both abundant and simple to qualify as a thalassogen. Rare elements, and molecules which are horribly complex, have a very low likelihood of being found in the oceanic state.

Apart from availability, there is one further basic requirement : The putative thalassogen must have a prominent liquid phase under the conditions typically encountered on planets. If the environment is such that the molecule has a hard time liquefying at all, clearly it will not be present in pelagic quantities on the surfaces of worlds.

Consider Mars, for example. At the surface of the red planet the atmospheric pressure is only 1% that on Earth.[2044] Under such conditions, any carbon dioxide frozen at the poles cannot melt to liquid CO2 upon heating. Quite the contrary, the "dry ice" there sublimes - that is, it passes directly from the solid to the gaseous state. This occurs even at more Earthlike pressures. Above 5.2 atm, though, CO2 is able to melt and form liquid carbon dioxide. Venus, whose atmosphere is mostly CO2 at nearly 100 atm, might have liquid carbon dioxide at its surface were it moved out to a cooler orbit and if the pressure could be maintained above 5.2 atm.

Consider the elemental abundances as noted in Table 5.3 above. Taking the cosmic values first, we see that two of the elements - the noble gases helium (He) and neon (Ne) - can be present in elemental form only. The most abundant atom, hydrogen (H), exists either in chemical combination (terrestrial worlds) or in large quantities in elemental form (as on the jovians). Oxygen (O), nitrogen (N), and sulfur each can achieve liquidity at temperatures that might be expected on planetary surfaces.

The elements silicon (Si), magnesium (Mg), and iron (Fe) unite with others on the list to form sulfides, oxides, nitrides and hydrides. The metal sulfides and oxides are extremely refractory, having melting/decomposing points above 1000 °C. They probably will not exist in liquid form on any normal planet for very long. Nitrides and hydrides of the aforementioned elements all tend to decompose either with elevated temperatures (i.e. before they have a chance to liquefy) or in the presence of water (which is likely to be ubiquitous anywhere in the universe). So none of these substances would make very good thalassogens.

Compounds comprised of hydrogen, oxygen, nitrogen, carbon and sulfur must also be considered. It has been argued that in a primarily hydrogenous environment, everything will tend to become as chemically hydrogenated as possible.[1399] Hence, oxygen will become water (H2O), nitrogen will go to ammonia (NH3), carbon will become methane (CH4), and sulfur will react to form hydrogen sulfide (H2S).

Many other simple compounds have been discovered, floating naturally in interstellar space, by radio astronomers in the last decade.[1002] These substances are observed in vast clouds, and include carbon monoxide (CO), sulfur dioxide (SO2), cyanogen (CN), hydrogen cyanide (HCN) and so forth.[521] A full consideration of all interstellar molecules discovered to date, and many other possibilities not yet detected, is unfortunately beyond the scope of this book.

Of course, oceans are not found in space but on planetary surfaces. Therefore, it is also relevant to consider the elemental abundances in the crusts of planets. We look for clues to additional compounds which might be generated by chemical reactions incident to planetary heating and volcanism, and which might be able to serve as thalassogens. From Table 5-1 we find only three elements - oxygen, hydrogen, and carbon - which are useful in this regard. Carbon dioxide (CO2) and water are the most common substances formed from these elements to be found on terrestrial worlds. Other molecules which might arguably arise under various planetary conditions include nitrogen dioxide (NO2) and carbon disulfide (CS2), although there are serious objections to both of these on reaction equilibrium grounds.

So much for availability. What about liquidity ? Even the coldest planet in our system (Pluto) has a surface temperature of at least 43 K.[2037] So the first three possibilities listed in Table 5.4 below - helium, hydrogen, and neon - can be ruled out because no reasonable world could be cold enough. But most of the remaining molecules could well be available as oceans on the surfaces of planets at the proper solar distances. (This is a gross oversimplification, of course, because relative abundances should also be taken into account.)

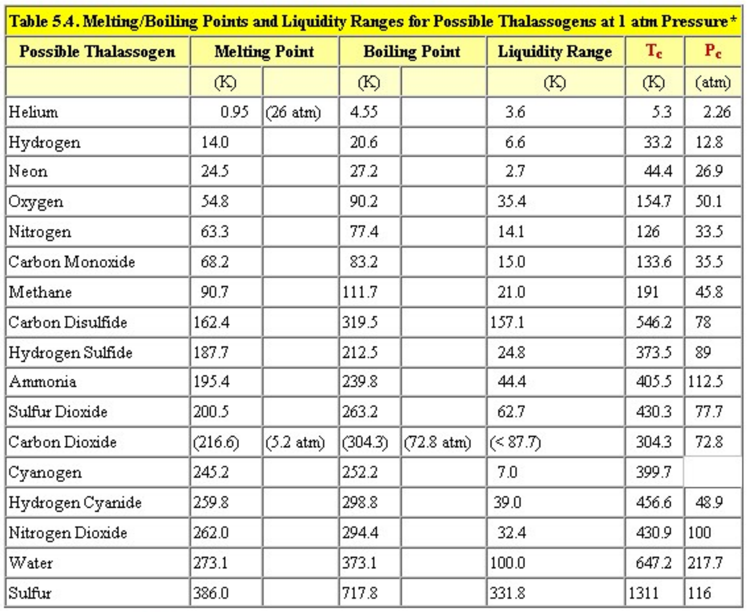


Table 5.4. Melting/Boiling Points and Liquidity Ranges for Possible Thalassogens at 1 atm Pressure*

Possible Thalassogen	Melting Point		Boiling Point		Liquidity Range	T_c	P_c
	(K)		(K)		(K)	(K)	(atm)
Helium	0.95	(26 atm)	4.55		3.6	5.3	2.26
Hydrogen	14.0		20.6		6.6	33.2	12.8
Neon	24.5		27.2		2.7	44.4	26.9
Oxygen	54.8		90.2		35.4	154.7	50.1
Nitrogen	63.3		77.4		14.1	126	33.5
Carbon Monoxide	68.2		83.2		15.0	133.6	35.5
Methane	90.7		111.7		21.0	191	45.8
Carbon Disulfide	162.4		319.5		157.1	546.2	78
Hydrogen Sulfide	187.7		212.5		24.8	373.5	89
Ammonia	195.4		239.8		44.4	405.5	112.5
Sulfur Dioxide	200.5		263.2		62.7	430.3	77.7
Carbon Dioxide	(216.6)	(5.2 atm)	(304.3)	(72.8 atm)	(< 87.7)	304.3	72.8
Cyanogen	245.2		252.2		7.0	399.7	
Hydrogen Cyanide	259.8		298.8		39.0	456.6	48.9
Nitrogen Dioxide	262.0		294.4		32.4	430.9	100
Water	273.1		373.1		100.0	647.2	217.7
Sulfur	386.0		717.8		331.8	1311	116

* At higher pressures these values become slightly higher. T_c, the critical temperature, is the highest temperature at which the compound stays liquefied (at any pressure). P_c, the critical pressure, is likewise the highest pressure for which the substance remains in the liquid state (at any temperature).

The lower the liquidity range, the faster the world must be spinning to maintain even temperatures. Cyanogen is particularly suspect on these grounds. As a general rule, the larger the range of liquidity the higher the probability of finding a planet whose temperatures fortuitously remain within the appropriate limits.

Xenologists are primarily interested in those thalassogens which might allow life to arise naturally on a planetary surface. We know that water, with its liquidity range of 100 K, has been capable of supporting and sustaining biology. The Hypothesis of Mediocrity allows us to take this as a minimum (or reasonable) value.

Using this standard, we see that water, carbon disulfide and sulfur all have liquidity ranges equal to or greater than 100 K. Another marginal possibility is carbon dioxide, and perhaps sulfur dioxide as well.[352] Ammonia is a very long shot.

For a million years, humanity has become accustomed to the shimmering blueness of the open seas. On a world with oceans of CO2, we would feel right at home. Carbon dioxide is a sparkling clear liquid slightly less dense than water. Oceans of it would possess the same evocative rich blueness as the seas of Earth. (Marine sulfur dioxide and ammonia should look similar.)

Carbon disulfide oceans would demand peculiar chemical conditions in the planetary crust to sustain them. CS2 is not believed to have existed in the primary atmospheres of any of the terrestrial worlds in our solar system. Nevertheless, as someone clever has remarked, absence of evidence is not evidence of absence. We've seen that the carbon disulfide molecule satisfies the most fundamental requirements of all thalassogens.

Oceans of this foul-smelling, poisonous substance would appear light-yellow in color in the shallower regions near coasts, due to the presence of colloidal sulfur particles. In deeper waters sunlight would begin to add a scattering component, causing a change of color to a peculiar shade of light-green. If there is any ammonia or hydrogen chloride around (even in trace amounts), simple chemical reactions would turn the sea a brilliant crimson.

Oceans of molten sulfur are the most fascinating of all, for they would change both color and viscosity regularly with oscillations in the planetary surface temperature. Between 386 K and about 430 K liquid sulfur is a thin, transparent, pale-yellow fluid. As the temperature increases from 430 K to 470 K, the substance becomes dark red in color and extremely thick and viscous. From 470 K to 500 °K the viscosity falls off but the color darkens from red to black. Above 500 K the sooty color remains, but the sea becomes thin and fast-flowing once again. Pelagic sulfur would make for a most interesting planetary environment indeed !